High precision QCD at hadron colliders

New techniques and results for perturbative calculations

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Outline

- Motivation and introduction
- Parton distribution functions
  - DGLAP kernels at NNLO
  - PDF errors
- Progress in next-to-leading order calculations
  - Higgs phenomenology
  - New techniques for NLO calculations
  - Merging NLO with parton showers
- Progress in NNLO calculations
  - New techniques for two-loop integrals
  - Understanding infrared divergences at NNLO
  - Phenomenology at NNLO
- Conclusions and outlook

The need for high precision

- Provides strong constraints on the SM and its extensions
  - Incredible success of the LEP, SLC Z-pole program
  - Extraction of M_W, m_t at the Tevatron
  - $\Rightarrow$ Precision EW data provides a vital experimental handle on new physics models
  - Become consistency checks, discriminators in presence of new physics
- Precise predictions for signals, backgrounds
- Measurements of NP parameters: masses, couplings
- Needed in absence of clear NP effect

Experimental prospects

- Great prospects for precision physics at hadron colliders
  - At the Tevatron
    - Each experiment has $\approx 220\,\mathrm{pb}^{-1}$ physics-ready data
    - Expect $2-3\,\mathrm{fb}^{-1}$ by LHC turn-on

$$\Delta m_t = \pm 5\,\mathrm{GeV} \to \pm(2.5-3)\,\mathrm{GeV}$$

$$\Delta M_W = \pm 60\,\mathrm{MeV} \to \pm(25-30)\,\mathrm{MeV}$$

  - At the LHC
    - In 1 year at $10\,\mathrm{fb}^{-1}$: over 10^7 $W, Z, t\bar{t}$ events $\Rightarrow \Delta\sigma_{stat} \ll 1\%$
    - Improved systematics (j, l energy scales) from high statistics samples
    - Reduction of luminosity error to $1-5\%$

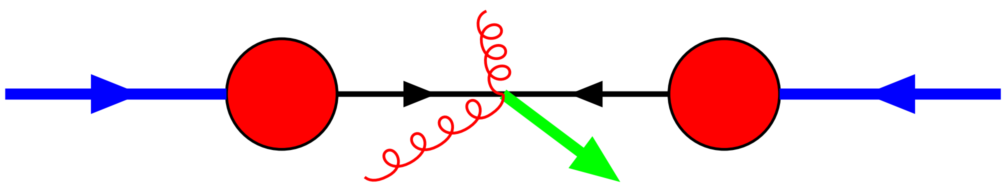
$\Rightarrow$ Percent level physics at the LHC!

- Talks by Dissertori, Huston, Wood at KITP conference on Collider Physics

Precision QCD

- Everything at hadron colliders involves QCD!
- Observables in hadronic collisions

$$N_{events} = L \int f_i(x_1, \mu^2)\, f_j(x_2, \mu^2)\, \sigma_{ij}(x_1, x_2, \mu^2)$$



- Require
  - luminosity measurement
  - parton distribution functions
  - scattering cross sections

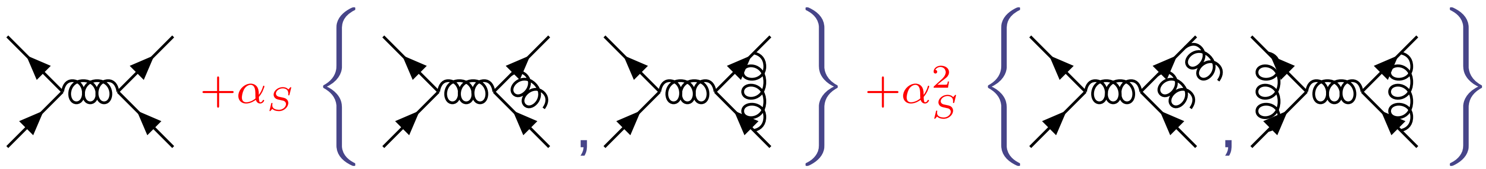
Components of a QCD calculation

- Extract luminosity from well-measured, understood processes
  - Total inelastic cross section at the Tevatron
  - W, Z cross sections at the LHC
  - $\Rightarrow$ Will quote $N_X = N_{W,Z} \left(\frac{\sigma_X}{\sigma_{W,Z}}\right)_{th}$
  - Theory predictions must account for acceptances
- Extract universal PDFs from experiment
  - DIS, jet production, fixed target Drell-Yan
  - Theory predictions must allow x dependence of $f(x, \mu^2)$ to be reconstructed
  - Evolution of momentum scale μ requires DGLAP kernels:

$$\frac{d\, f(x, \mu^2)}{d \ln \mu^2} = \sum_{n=0} \left(\frac{\alpha_S}{4\pi}\right)^n P^{(n)}(x) \otimes f(x, \mu^2)$$

Cross sections in QCD

- $\sigma = \sigma_0 \{1 + \alpha_S (l + \sigma_1) + \alpha_S^2 (l^2 + l + \sigma_2) + \mathcal{O}(\alpha_S^3)\}$



- Strong coupling constant not small: $\alpha_S(M_Z) \approx 0.12$

$\Rightarrow$ higher order corrections important

- Contains scales $l = \ln(\mu^2/Q^2)$
  - UV behavior: renormalization scale dependence (μ_R)
  - IR behavior: factorization scale dependence (μ_F)
  - Scales are arbitrary: $\frac{d\sigma}{d\mu} = 0$

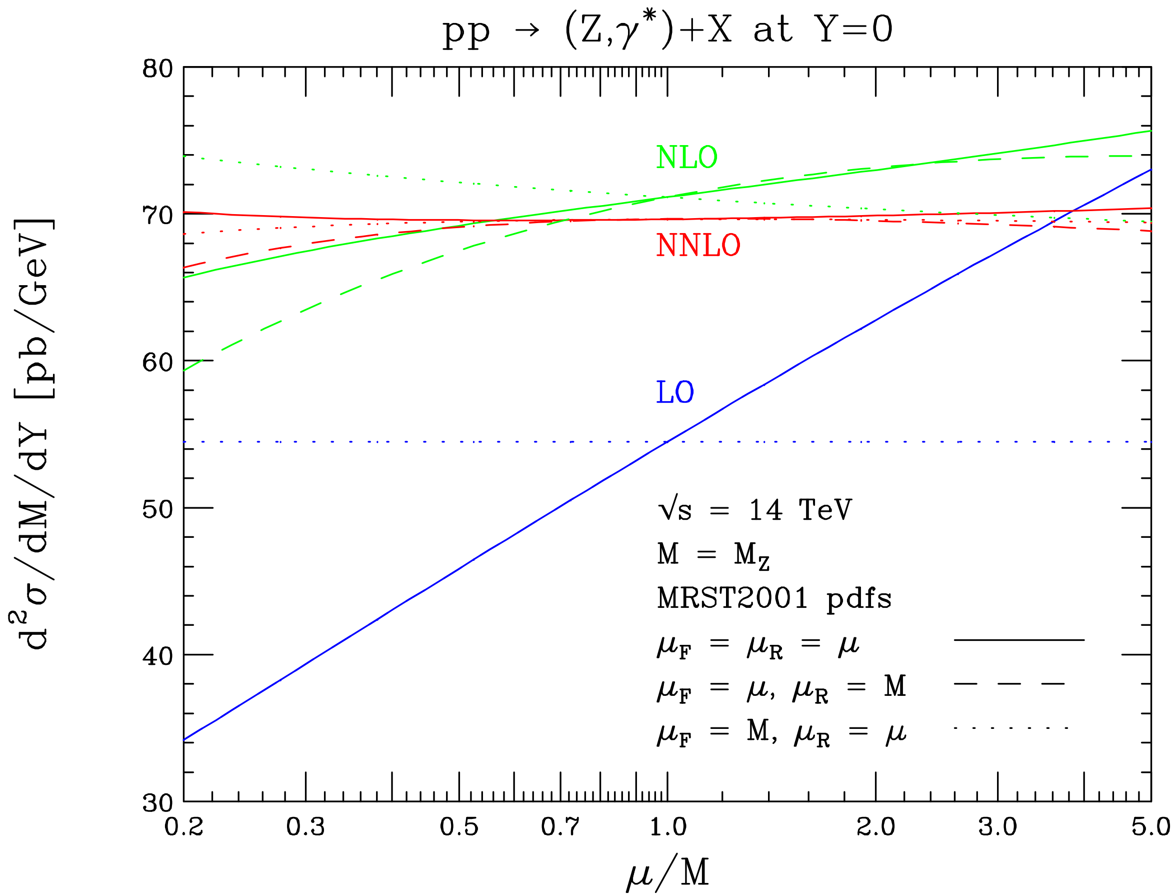
  $\Rightarrow$ but truncation of expansion at $\mathcal{O}(\alpha_S^n)$ induces a scale dependence of $\mathcal{O}(\alpha_S^{n+1})$
  - Residual scale dependences provide estimate of neglected higher order effects

From LO to NNLO

- LO
  - No quantitative estimate of cross section
  - Few partonic channels open in initial state
  - $\Rightarrow$ poor estimate of kinematics, dependence on PDFs
  - Few partons in final state $\Rightarrow$ poor modeling of jets
- NLO
  - First quantitative estimate of cross section
  - Better modeling of kinematics, final-state structure
- NNLO
  - Residual scale dependences small
  - Allows precision predictions

High precision theory

- In the best of all possible worlds:



Scale variations:

- 35% at LO
- 5% at NLO
- $<$ 1% at NNLO

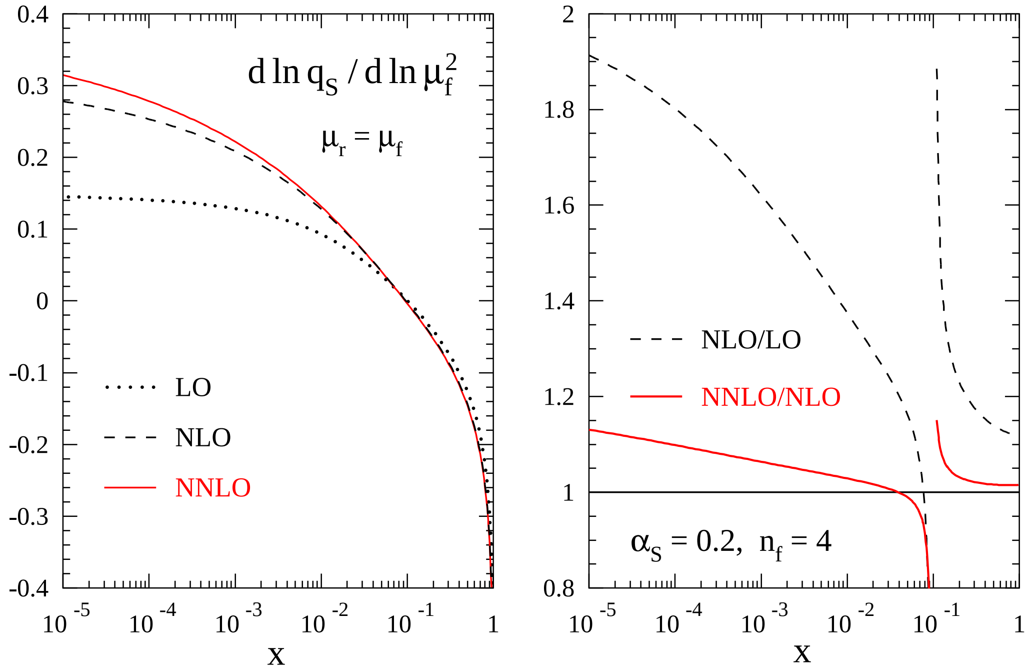
Parton distribution functions

Parton distribution functions

- Method of extraction
  - Choose a data set for a given process (DIS, Drell-Yan, jets)
  - Write theory prediction as a convolution of PDFs and hard scattering cross section, at a given order
  - Extract PDFs, to the given order
  - Evolve to other Q^2 with the DGLAP equation
- Several different sets available: CTEQ, MRST, Alekhin, . . .
  - "NNLO" PDFs provided by MRST, Alekhin
- Sources of error
  - In the evolution: DGLAP kernels not known to needed order in α_S
  - In the fitting: experimental errors, imprecise hard scattering cross sections, . . .

DGLAP evolution

- Full calculation of NNLO kernels recently completed (Moch,Vermaseren,Vogt)



- Corrections $5-10\%$ for $x < 10^{-3}$
- New $\ln^4 x$ LL stucture
- μ variation $1-2\%$ for $x > 10^{-3}$
  $< 8\%$ for $x < 10^{-3}$
- $\mathrm{N}^3\mathrm{LO}$ likely important for small x

- Agrees with approximate result based on first few moments
  - "NNLO" PDFs of MRST, Alekhin likely okay for most phenomenological purposes

PDF errors

- Recent efforts to estimate PDF errors on W, Z, H production
  - Variations within a PDF set are small

  $\Rightarrow$ $\delta\sigma_W^{NNLO} = \pm 4\%$, $\delta\sigma_H^{NNLO} = \pm 3\%$ for MRST, similar for Alekhin
  - Variations between sets larger

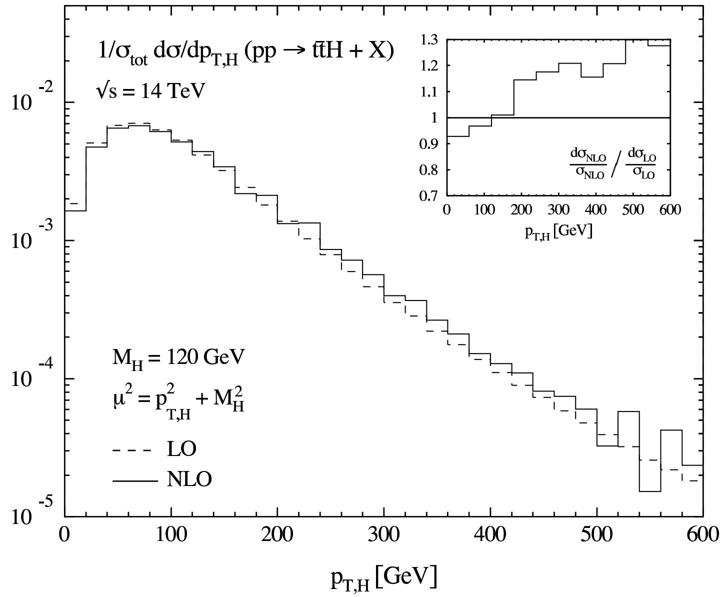
  $\Rightarrow$ $\approx 15\%$ for H production (Djouadi, Ferrag)
  (at NLO, but quoted variations within set were $\approx 5 - 10\%$)

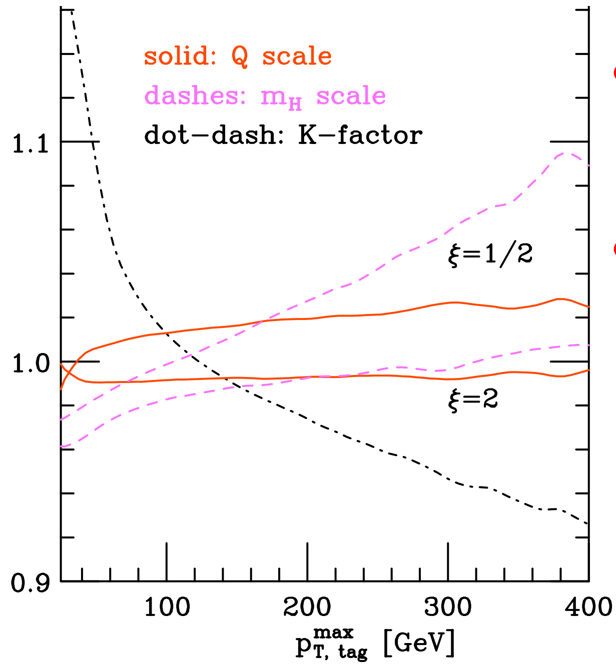
  $\Rightarrow$ $\leq 8\%$ for W, Z production at the LHC, at NNLO
- In the future (?)
  - Use full NNLO kinematics for Drell-Yan cross section in fit (only inclusive K-factor)
  - Jet cross sections at NNLO
  - Add Drell-Yan to Alekhin (only DIS, others global)
  - Use LHC data to constrain

Progress in NLO calculations

Advances in NLO Phenomenology

- Several studies of Higgs physics at the LHC
  - $pp \longrightarrow t\bar{t}H, b\bar{b}H$: Beenakker *et. al.*; Dawson *et. al.*
  - $pp \longrightarrow jjH$ (WBF): Figy, Oleari, Zeppenfeld; Berger, Campbell





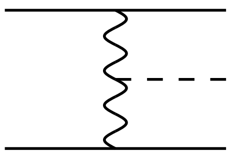
- K-factors vary with kinematics
- Uncertainties:
  WBF: $\pm 6 - 10\%$
  $t\bar{t}H$: $\pm 15 - 20\%$

- No longer just discovery; detailed analysis of couplings, etc.

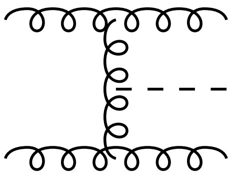
Extracting Higgs couplings

- Measure HWW coupling with WBF (ATLAS; Berger, Campbell)

Signal: WBF

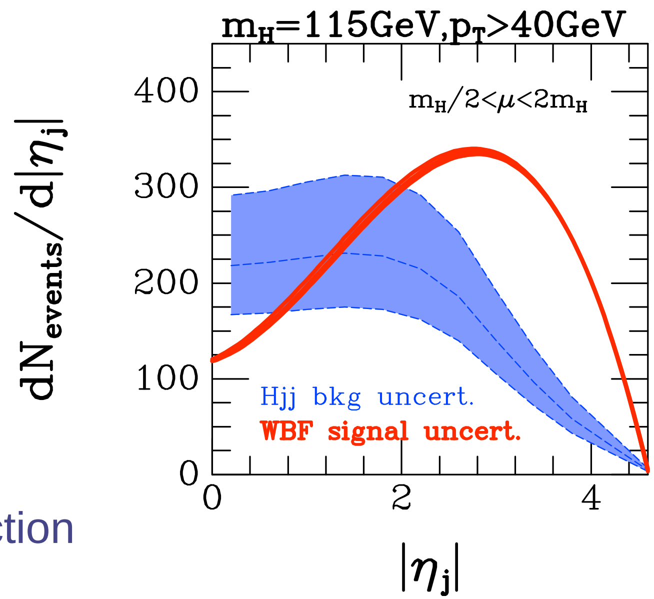


Background: QCD Hjj



$\Rightarrow$ Higgs production now a background!

- Separate S, B with kinematics
- Uncertainty dominated by $\delta S/S, \delta B/B$
  $\delta B/B = \pm 20\%$, $\delta S/S = \pm 4\%$ (ATLAS)
  $\delta B/B = \pm 30\%$, $\delta S/S = \pm 10\%$ (BC)
- Estimate $\delta g/g \approx 10\%$ after $200\,\mathrm{fb}^{-1}$ (BC)
- Background known only at LO
  $\Rightarrow$ need NLO computation of QCD Hjj production



Wishful thinking

- Missing many needed NLO computations   Campbell

An experimenter's wishlist

- Hadron collider cross-sections one would like to know at NLO

Run II Monte Carlo Workshop, April 2001

Single boson	Diboson	Triboson	Heavy flavour
$W + \leq 5j$	$WW + \leq 5j$	$WWW + \leq 3j$	$t\bar{t} + \leq 3j$
$W + b\bar{b} + \leq 3j$	$WW + b\bar{b} + \leq 3j$	$WWW + b\bar{b} + \leq 3j$	$t\bar{t} + \gamma + \leq 2j$
$W + c\bar{c} + \leq 3j$	$WW + c\bar{c} + \leq 3j$	$WWW + \gamma\gamma + \leq 3j$	$t\bar{t} + W + \leq 2j$
$Z + \leq 5j$	$ZZ + \leq 5j$	$Z\gamma\gamma + \leq 3j$	$t\bar{t} + Z + \leq 2j$
$Z + b\bar{b} + \leq 3j$	$ZZ + b\bar{b} + \leq 3j$	$WZZ + \leq 3j$	$t\bar{t} + H + \leq 2j$
$Z + c\bar{c} + \leq 3j$	$ZZ + c\bar{c} + \leq 3j$	$ZZZ + \leq 3j$	$t\bar{b} + \leq 2j$
$\gamma + \leq 5j$	$\gamma\gamma + \leq 5j$		$b\bar{b} + \leq 3j$
$\gamma + b\bar{b} + \leq 3j$	$\gamma\gamma + b\bar{b} + \leq 3j$		
$\gamma + c\bar{c} + \leq 3j$	$\gamma\gamma + c\bar{c} + \leq 3j$		
	$WZ + \leq 5j$		
	$WZ + b\bar{b} + \leq 3j$		
	$WZ + c\bar{c} + \leq 3j$		
	$W\gamma + \leq 3j$		
	$Z\gamma + \leq 3j$		

Wishful thinking

- Missing many needed NLO computations — Campbell

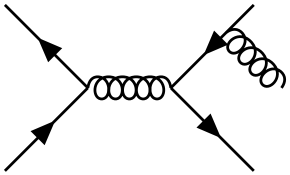
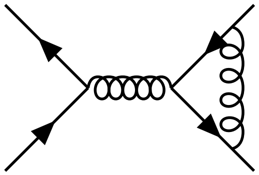
Theoretical status

- Much smaller jet multiplicities, some categories untouched

Single boson	Diboson	Triboson	Heavy flavour
$W+\leq 2j$	$WW+\leq 0j$	$WWW+\leq 3j$	$t\bar{t}+\leq 0j$
$W+b\bar{b}+\leq 0j$	$WW+b\bar{b}+\leq 3j$	$WWW+b\bar{b}+\leq 3j$	$t\bar{t}+\gamma+\leq 2j$
$W+c\bar{c}+\leq 0j$	$WW+c\bar{c}+\leq 3j$	$WWW+\gamma\gamma+\leq 3j$	$t\bar{t}+W+\leq 2j$
$Z+\leq 2j$	$ZZ+\leq 0j$	$Z\gamma\gamma+\leq 3j$	$t\bar{t}+Z+\leq 2j$
$Z+b\bar{b}+\leq 0j$	$ZZ+b\bar{b}+\leq 3j$	$WZZ+\leq 3j$	$t\bar{t}+H+\leq 0j$
$Z+c\bar{c}+\leq 0j$	$ZZ+c\bar{c}+\leq 3j$	$ZZZ+\leq 3j$	$t\bar{b}+\leq 0j$
$\gamma+\leq 1j$	$\gamma\gamma+\leq 1j$		$b\bar{b}+\leq 0j$
$\gamma+b\bar{b}+\leq 3j$	$\gamma\gamma+b\bar{b}+\leq 3j$		
$\gamma+c\bar{c}+\leq 3j$	$\gamma\gamma+c\bar{c}+\leq 3j$		
	$WZ+\leq 0j$		
	$WZ+b\bar{b}+\leq 3j$		
	$WZ+c\bar{c}+\leq 3j$		
	$W\gamma+\leq 0j$		
	$Z\gamma+\leq 0j$		

Computing cross sections at NLO

- Two components of an NLO calculation:

Real:  Virtual: 

  - Obtain a cross section in the form:

    $\sigma_{NLO} = \int d\Phi_n \left(\sigma_B + \alpha_S \sigma_{virt}\right) + \alpha_S \int d\Phi_{n+1} \sigma_{real}$

- Dealing with divergences
  - UV: cancel with coupling constant renormalization
  - IR: typically use dipole subtraction (Catani, Seymour)
    - Introduce counterterm D which reproduces IR divergences of σ_{real}:

      $\sigma_{NLO} = \int d\Phi_n \left(\sigma_B + \alpha_S \left[\sigma_{virt} + D_I\right]\right) + \alpha_S \int d\Phi_{n+1} \left[\sigma_{real} - D\right]$,

      with $D_I = \int d\Phi_1 \, D$
    - Cancel divergences analytically in $\sigma_{virt} + D_I = \sigma_{virt}^{fin}$
    - $\sigma_{real} - D$ is pointwise finite, numerically integrable

Obstacles at NLO

- Two major sticking points at NLO:
  - Going beyond $2 \to 3$ processes
  - Large number of processes needed
- Root cause: multi-leg ($N \geq 5$) virtual integrations
  - Many scales ($s_{ij}, M_W, m_H, m_t, \ldots$)

  $\Rightarrow$ expressions become enormous

  $\Rightarrow$ large numerical cancellations between terms

  $\Rightarrow$ different integrals needed for each process
  - Many singular regions: soft, collinear, UV, thresholds, spurious singularities, . . .

  $\Rightarrow$ singular subtractions not as well understood as for real emission contributions
- Goal: automated, general method, as for real contributions
  - Also want a flexible approach to be ready for LHC analyses

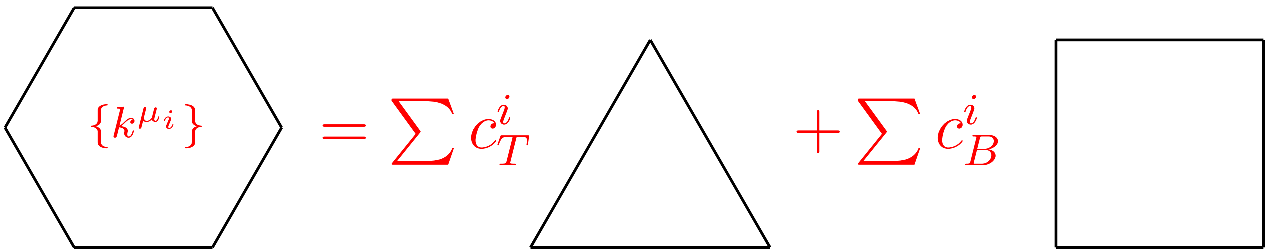
Schematic of NLO virtual corrections

- What we get from Feynman diagrams for $2 \to N-2$:

$$I_N^m = \int d^dk \, \frac{k^{\mu_1} \ldots k^{\mu_m}}{[(k+q_1)^2 - m_1^2] \ldots [(k+q_N)^2 - m_N^2]}$$

  - Large number of integrals which aren't independent

  $\Rightarrow$ can reduce tensor structure, use recurrence relations to obtain a minimal set of basis scalar integrals



- c^i lengthy for large N, many scales
- $c^i \sim 1/p_a \cdot p_b$
- Expressions for basis integrals complicated

- How much do we do analytically, how much numerically?

Automating NLO virtual corrections

- Hybrid approach (Giele, Glover)
  - Reduce divergences to triangle integrals
  - Solve the remaining recurrence relations numerically
  - Completely avoid lengthy c^i
- Numerical approach (Nagy, Soper)
  - Define counterterms for UV, IR, collinear singularities graph-by-graph
  - Similar to dipole subtraction for real contributions
  - Integrate counterterms analytically, feed remainder directly to numerical integration
- Other approaches suggested (Binoth *et. al.*, . . .)

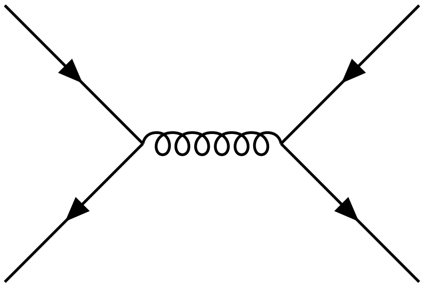
$\Rightarrow$ No implementation yet of any method

Merging parton showers with NLO

Merging parton showers with NLO

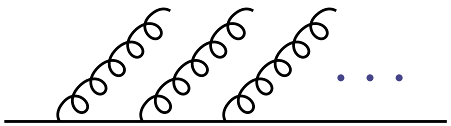
- Experimentalists typically use shower MCs for predictions

Begin with:



$\Rightarrow$

MC generates shower for each line:



- Emissions controlled by Sudakov form-factor:

  $\Delta(x, x_M) = \exp\left(-\alpha_S \int_x^{x_M} d\Phi\, Q(\Phi)\right)$

- $Q(\Phi)$ encodes behavior of the soft/collinear emissions
- Typically use several approximations: no shower interference, angular ordering, . . .

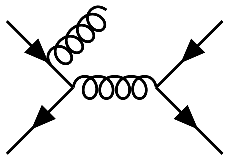
Fixed order vs. shower MCs

- Fixed order
  - $+$ Systematic expansion in α_S
  - $+$ Based on exact matrix elements; describes hard/wide angle emissions well
  - $-$ Relatively few partons in final state; no way to hadronize
  - $-$ Not available beyond leading order for all processes; when available, tend to be spread among different codes
- Shower Monte Carlos
  - $+$ Generate many partons in the final state; access to hadronization
  - $+$ Many processes available in a few codes (HERWIG, PYTHIA)
  - $-$ Doesn't describe hard/wide angle emissions correctly
  - $-$ Doesn't systematically include higher order corrections $\Rightarrow$ can't do precision physics

$\Rightarrow$ Want the advantages of both approaches

Merging parton showers with NLO

- Can't just use NLO matrix elements in the MC
  - $\sigma_{NLO} = \int d\Phi_n \left(\sigma_B + \alpha_S \left[\sigma_{virt} + D_I\right]\right) + \alpha_S \int d\Phi_{n+1} \left[\sigma_{real} - D\right]$

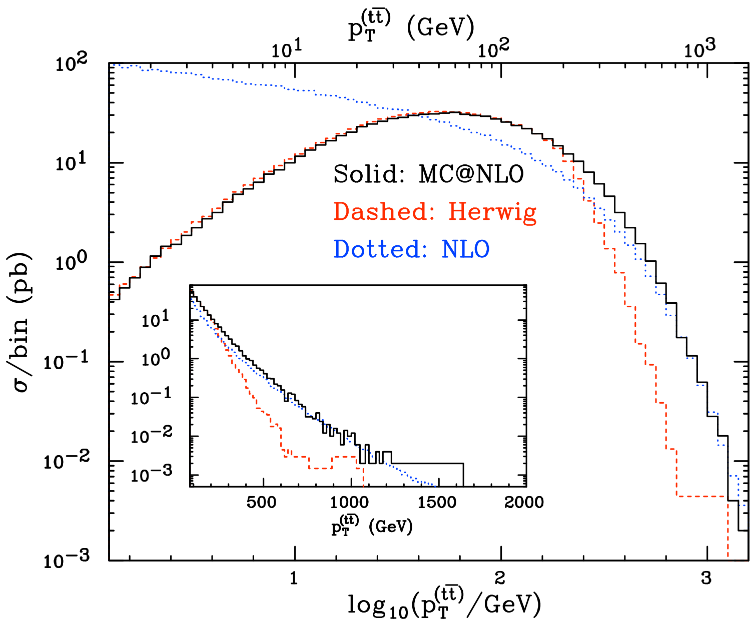
    $\sigma_{real} = \Bigg|$  $+ \cdots \Bigg|^2$ $\Rightarrow$ NLO corrections already include some gluon emissions; double-counting

  - Incompatible with subtraction formalism for NLO corrections
    - D is the soft/collinear limit of σ_{real} $\Rightarrow$ has only n-body kinematics
    - Generate different showers for D, σ_{real}

    $\Rightarrow$ only cancel divergences after generating showers for each piece

MC@NLO

- Use the MC itself as a counterterm (Frixione, Webber)
  - $Q(\Phi)$ encodes emission singularities $\Rightarrow$ use it as an additional counterterm
  - $Q(\Phi)$, σ_{real} coincide in singular phase space regions, so weights are finite
  - Also removes double counting of real emissions



- Smoothly matches soft/collinear (MC) and hard (NLO) regions
- Works for most observables; MC not a local counterterm for large-angle soft emissions

Progress in NNLO calculations

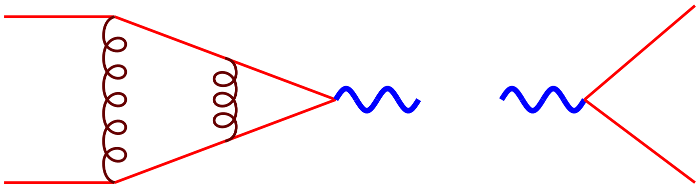
The NNLO revolution

- Tremendous progress recently in NNLO computations
  - New computational techniques for two-loop integrals
  - Better understanding of singular structure of real radiation
  - Many new phenomenological results
- Is NNLO necessary?
  - Reduced scale dependence
  - More partons $\Rightarrow$ more realistic
  - Several concrete physical applications that require NNLO:
    - Higgs production at hadron colliders
    - Drell-Yan (luminosity monitor, PDF measurements)
    - Jet production at hadron colliders (PDFs, α_S extraction)
    - Jet production at e^+e^- colliders

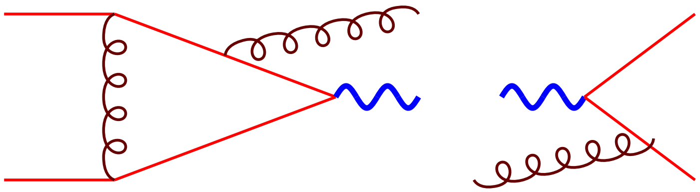
$$\alpha_S(M_Z) = 0.1202 \pm 0.0003(\mathrm{stat}) \pm 0.0009(\mathrm{sys}) \pm 0.0009(\mathrm{had}) \pm 0.0047(\mathrm{th})$$

Anatomy of a NNLO calculation

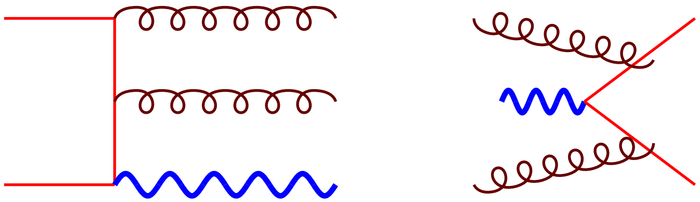
- Virtual-Virtual



- Real-Virtual



- Real-Real

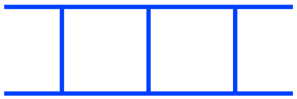
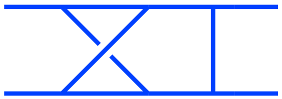


Two-loop integrals

- Loop integrals satisfy recurrence relations arising from Poincare invariance
  - Use integration-by-parts to derive (Chetyrkin, Tkachov)
  - $I\left[\nu_1, \nu_2\right] = \int d^D k \frac{1}{[k^2]^{\nu_1} [(k+p)^2]^{\nu_2}}$
  - Set $\int d^D k \frac{\partial}{\partial k_\mu} \frac{k^\mu}{k^2 (k+p)^2} = 0$
  - Derive $I\left[1, 2\right] = -\frac{D-3}{p^2} I\left[1, 1\right]$
- Reduce to a small set of master integrals
- Two things to do:
  - Reduce the integrals appearing in the matrix elements to master integrals
  - Calculate the master integrals

Recent virtual progress

- Until recently, missing the master integrals

  $\Rightarrow$ calculated by Smirnov, Tausk

- New methods for solving systems of recurrence relations
  - Old-fashioned method: manipulate recurrence relations manually

  $\Rightarrow$ avoids introducing unneeded integrals, but rapidly becomes difficult
  - Algorithmic method (Laporta):
    - Fully automated method of iteratively solving recurrence relations
    - Very general procedure applicable to a large class of problems
    - Efficient implementation now publicly available (Anastasiou, Lazopoulos)

Available two-loop amplitudes

- Recently computed amplitudes for $2 \to 2$ processes:
  - Two-loop Bhabha scattering in massless QED — Bern, Dixon and Ghinculov
  - All two-loop $2 \to 2$ QCD processes. — Anastasiou, Glover, Oleari and Tejeda-Yeomans; Bern, De Freitas, and Dixon
  - $\gamma\gamma \to \gamma\gamma$ — Bern, Dixon, De Freitas, A. Ghinculov and H.L. Wong
  - $gg \to \gamma\gamma$. (Background to Higgs decay.) — Bern, De Freitas, Dixon
  - $\bar{q}q \to \gamma\gamma$, $\bar{q}q \to g\gamma$, $e^+e^- \to \gamma\gamma$ — Anastasiou, Glover and Tejeda-Yeomans
  - $e^+e^- \to 3$ partons — Garland, Gehrmann, Glover, Koukoutsakis and Remiddi; Moch, Uwer, Weinzierl
  - DIS 2 jet and $pp \to W, Z + 1$ jet — Gehrmann and Remiddi

Recent real progress

- Currently the sticking point in completing NNLO calculations
  - Until recently, no direct calculation of $e^+e^- \to 2$ jets at NNLO!
  - Tree graphs, so what's the problem?

  $\Rightarrow$ Understanding their singular structure when partons become unresolved
  How do we extract their IR singularities before integrating over phase space?

- Two ways to approach the problem:

  (1) General method which aims for a complete understanding of IR structure

  (2) Ask for information about restricted, "semi-inclusive" quantities

IR structure at NNLO

- Understanding IR singularities at NNLO
  - Would allow for completely differential NNLO calculations
  - Extensions of the subtraction method to NNLO (Campbell, Glover; Kosower; Weinzierl; Gehrmann-De Ridder, Gehrmann, Glover; Kilgore)

$$\sigma_{NNLO} = \int d\Phi_n \left(\sigma^{(0)} + \alpha_S \left[\sigma_v^{(1)} + D^{(1)}\right] + \alpha_S^2 \left[\sigma_v^{(2)} + D^{(2)}\right]\right) + \alpha_S \int d\Phi_{n+1} \left[\sigma_r^{(1)} - D^{(1)}\right] + \alpha_S^2 \int d\Phi_{n+2} \left[\sigma_r^{(2)} - D^{(2)}\right]$$

  - Integrate the $D^{(1,2)}$ analytically, and the remainder numerically
  - $D^{(2)}$ must incorporate many limits: 3 collinear, 2 pairs collinear, 1 soft + 2 collinear, ...
  - Alternative approach: Φ_n structure permits an automated extraction of IR divergences (Binoth, Heinrich; Anastasiou, Melnikov, FP)
    - Derive a series in $1/\epsilon$ with numerical coefficients
    - Don't need any analytic integrations
    - Don't need to consider singular limits separately

Semi-inclusive obervables at NNLO

- Can adapt multi-loop techniques to phase space integrals (Anastasiou, Melnikov)

$$\sigma_{\alpha\beta\to 1\ldots n} \propto \int \left[\prod_{i=1}^{n} d^d q_i \delta\left(q_i^2 - m_i^2\right)\right] \delta\left(p_{\alpha\beta} - q_{1\ldots n}\right) \left|\mathcal{M}_{\alpha\beta\to 1\ldots n}\right|^2$$

  - Cutkosky rules: $\delta\left(q_i^2 - m_i^2\right) \Rightarrow \frac{1}{q_i^2 - m_i^2 - i\epsilon} - \frac{1}{q_i^2 - m_i^2 + i\epsilon}$
  - Maps phase space integrals $\Rightarrow$ cut loop integrals
  - Can extend to differential quantities (Anastasiou, Dixon, Melnikov, FP)
  - Rapidity distributions ($u = \frac{x_1}{x_2} e^{-2Y}$):

$$\frac{d\sigma}{dY} \propto u \int \left[\prod_{i=1}^{n} d^d q_i \delta\left(q_i^2 - m_i^2\right)\right] \delta\left(u - \frac{p_1 \cdot P_h}{p_2 \cdot P_h}\right) \delta\left(p_{\alpha\beta} - q_{1\ldots n}\right) \left|\mathcal{M}_{\alpha\beta\to 1\ldots n}\right|^2$$

  - Make the same replacement for the rapidity constraint

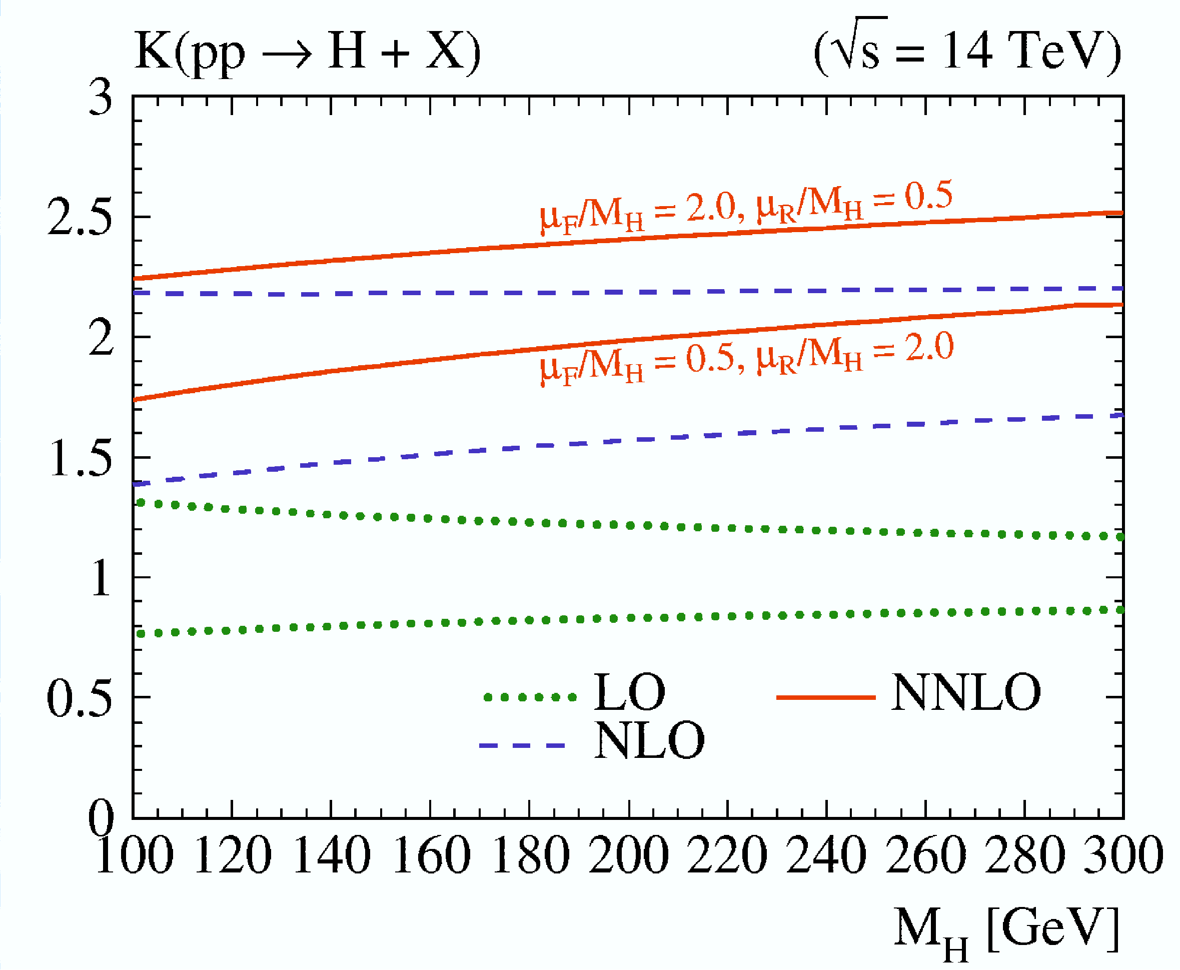
$\Rightarrow$ Introduce a fictitious particle, whose mass-shell condition $\Leftrightarrow$ phase-space constraint

  - In the fully differential limit, recurrence relations provide no information

Higgs production at NNLO

- Several recent NNLO calculations

  (Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, Smith, van Neerven)



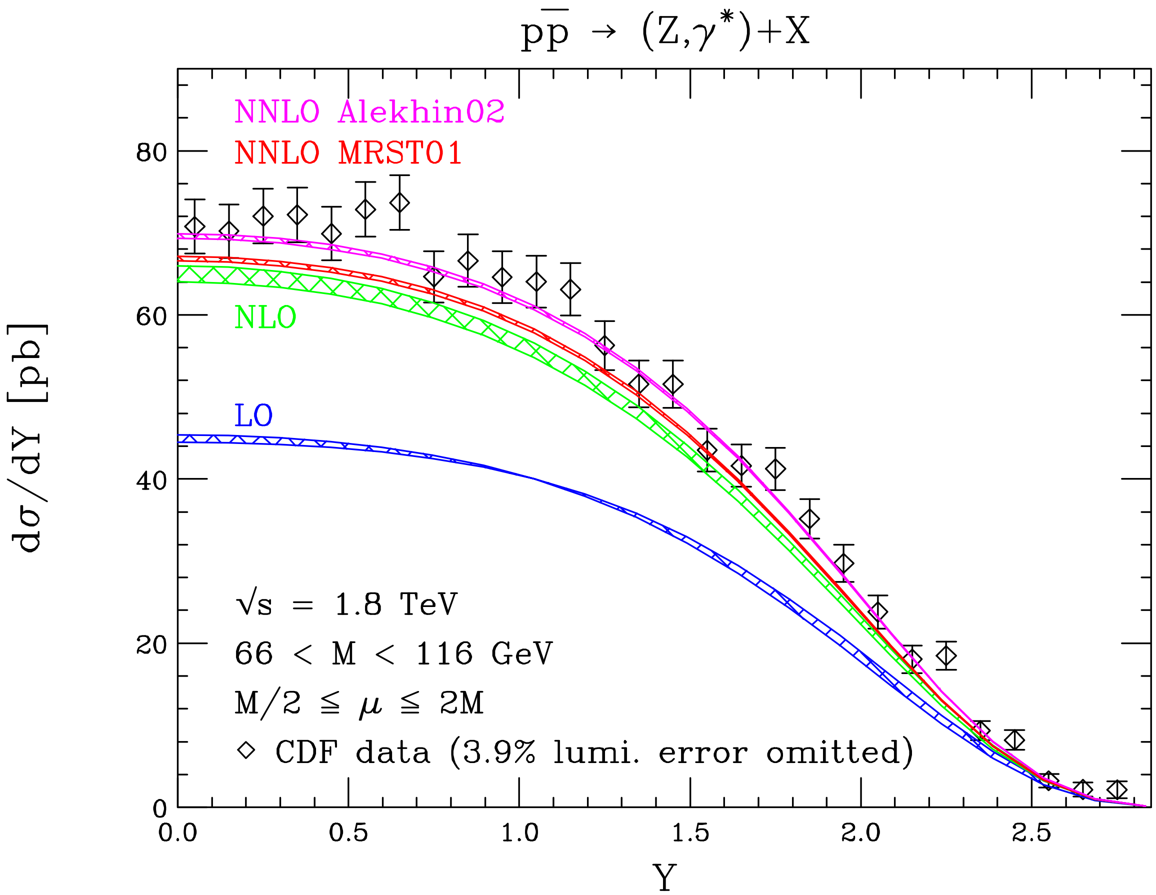
- $30 - 40\%$ residual scale dependence at NLO
- NLO corrections increase LO result by $70 - 80\%$

$\Rightarrow$ Does the series converge?

- 20% residual scale dependence at NNLO
- NNLO corrections are $\leq 30\%$

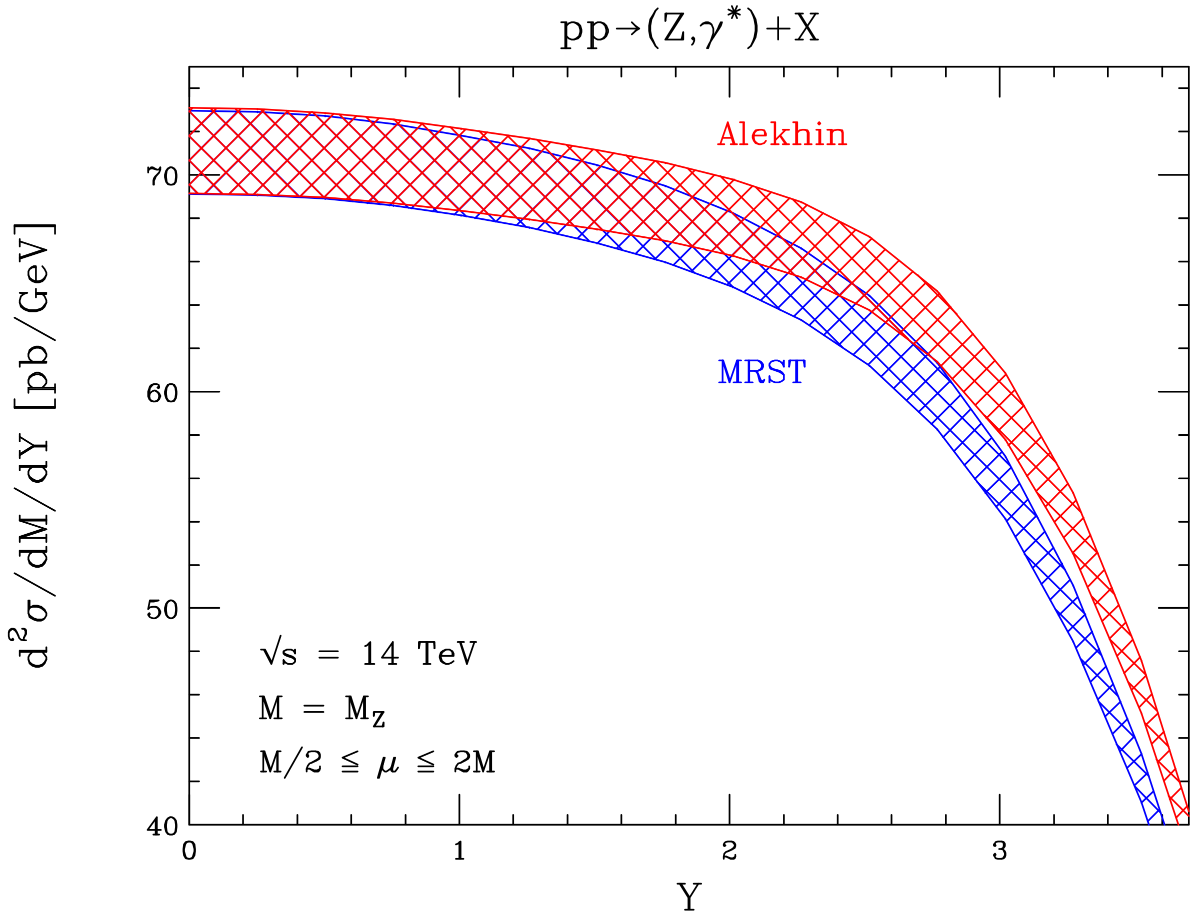
Drell-Yan rapidity distributions

- First complete differential result at NNLO
  (Anastasiou, Dixon, Melnikov, FP)



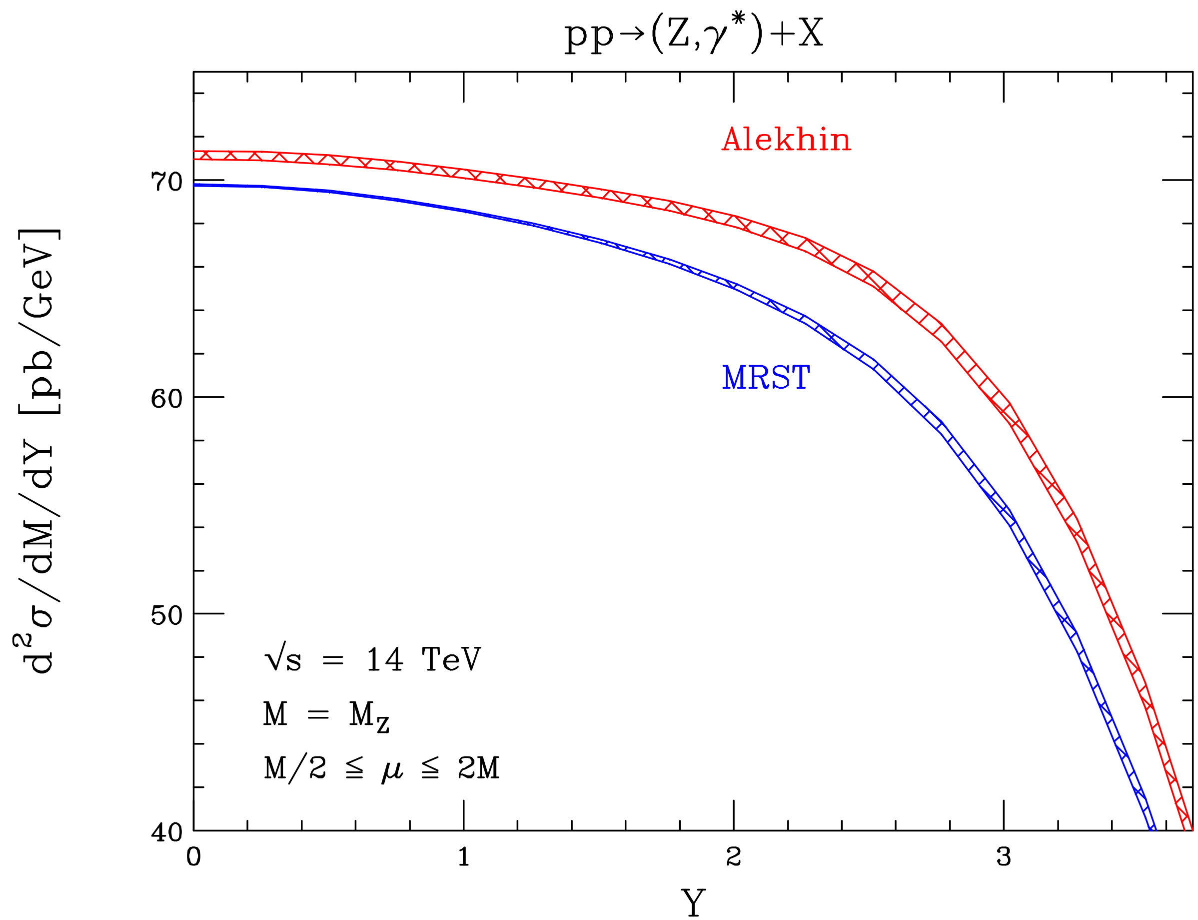
- NNLO corrections increase NLO result by 3-5%
- Scale variations 3-6% at NLO, $< 1\%$ at NNLO
- Drell-Yan now a high precision probe of QCD

PDFs with NLO Drell-Yan



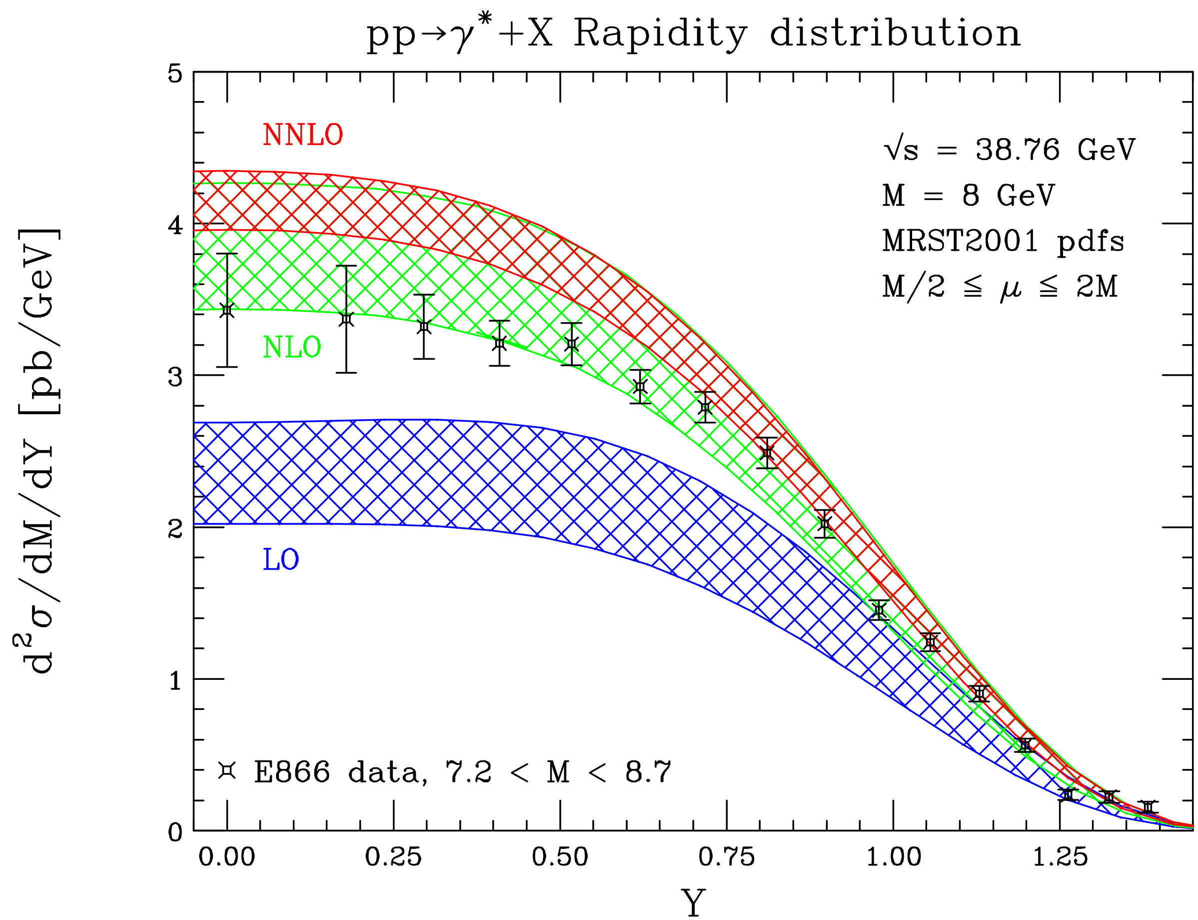
- Alekhin parameterization fits only to DIS data; MRST fits to DIS, DY, jets
- Scale variations render undistinguishable at NLO

PDFs with NNLO Drell-Yan



- Alekhin parameterization fits only to DIS data; MRST fits to DIS, DY, jets
- Scale variations render undistinguishable at NLO
- Resolved at NNLO

Fixed target (E866)



- Strong constraint on $\bar{q}$ and $x \to 1$ q_{val} distribution functions
- Reduced μ dependence at NNLO reveals discrepancy with data

$\Rightarrow$ Tune $\bar{q}$ PDFs

Conclusions

- Exciting prospects for precision physics at future colliders
- Need theoretical work to fully utilize results
- Much more to do before LHC start
- Expect continued progress on several fronts
  - Practical implementations of algorithms for NLO calculations
  - Further development of NNLO subtraction scheme
  - First completely differential NNLO calculations for high-value observables ($W, Z, H, \ldots$)
- Not yet just turning the crank

$\Rightarrow$ room for new ideas!